III.D.5 An Investigation to Resolve the Interaction between Fuel Cell, Power Conditioning System and Application Load

Objectives

- Comprehensive experimental validation and parametric study of the effects of electrical feedbacks on PSOFC and PSOFC stack.
- Design of optimal and reliable power-management control system for mitigation of electrical-feedback effects on PSOFC and to maximize the efficiency.
- Balance-of-plant subsystem (BOPS) parametric optimization for optimal start-up, steady-state, and transient performance.
- Investigation of the impacts of the electrical feedback on the long-term degradation of the SOFC stack.

Accomplishments

- Completed experimental validation of several electrical feedback effects, such as, the load transients, multiple load transients, low-frequency ripple, etc.
- Conducted comprehensive parametric analysis of the effects of the load transient, low-frequency (LF) ripple, power factor, and harmonic distortion on the performance and efficiency of the stack.
- Developed a ripple-mitigating highly efficient PES, which can be used for experimental validation of modeling data by integrating with an experimental PSOFC stack.
- Development of power-management control strategies for PES and BOPS to enhance the performance and life of the PSOFC.

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Introduction

Planar solid oxide fuel cell stacks (PSOFCSs), in PSOFC based power-conditioning systems (PCSs), are subjected to electrical feedbacks due to the switching power electronics and the application of loads. These feedbacks (including load transient, current ripple due to load power factor and inverter operation, and load harmonic distortion) affect the electrochemistry [1-5] and the thermal properties [6] of the planar cells thereby potentially deteriorating the performance and reliability of the cells. Therefore, a comprehensive spatio-temporal simulation model of the SOFC PCS is essential to investigate the potentially degrading impacts of such electrical feedbacks on the PSOFC. To ascertain the efficacy of any such model, and for accurate prediction of the impacts of the electrical feedbacks, experimental validation of the models both in steady state and transience is required.

The parametric study of these electrical feedbacks can only predict the short-term degrading impacts on the PSOFCS. However, for the PSOFC PCS to meet the lifetime specifications, a long-term study needs to be conducted which can predict the deteriorating impact of some of the effects in the long term. Since it is impossible to conduct long-term (order of 1,000 hours) study of the large-scale simulation model of the PSOFC PCS, this study needs be conducted experimentally.

The slow response time of the BOPS mechanical system as compared to the fuel-cell electrochemistry and the PES has been a major concern for fuel cell system designers [7-8]. To avoid the low reactant condition, energy buffering devices like a battery, which would provide the additional energy immediately to the load during the load transient, is needed in conjunction with the fuel cell stack [7]. To optimize the size and response of the battery while eliminating the degrading impacts of the load transient on the stack, a control strategy needs to be developed which would control the energy flow between the energy generator (fuel cell stack) and the energy buffering device (battery).

Approach

A detailed study is conducted on the electrical-feedback effects (including load transients, current ripple variations due to load power factor and inverter operation, and load harmonic distortions) that have an impact on the electrochemistry and the thermal properties of the SOFC, thereby affecting the performance and reliability of the cells. Subsequently, detailed experimentation is carried out to validate the simulation data on interaction analyses.

The test bed consists of a stack prototype with the power electronics system, as shown in Figure 1. The stack consists of 25 planar cells in series. In the stack, all the planar cells are mounted in a single manifold. Each cell has an electro-active area of 64 cm^2.

Using this validated model, parametric analyses on the impacts of transience, power factor, and distortion of the application load as well as LF current ripple is conducted. The study clearly establishes that sizing of the SOFC stack needs to take into account ripple magnitude and input-filter design simultaneously.

To study the effect of two of the important electrical feedbacks in the long term, two sets of experimental test beds are built using the similar cells used for the transient experiment. The degradation study of ripple is conducted on a 5-cell stack connected to a boost converter, and a 5-cell stack connected to the constant load. The duty ratio of the switch of the boost converter is modulated sinusoidally at 60 Hz. The average current drawn from both the stacks are kept at approximately 13 A. The open circuit voltage of the 5-cell stack is 5.087 V. Similarly, for the study the long-term degradation effect due to the load transient, a 25-cell planar stack is connected to a programmable DC-DC converter followed by a load resistance. The DC-DC converter is programmed to draw 13 A current for first 20 minutes and 2.2 A for the next 10 minutes in every half an hour. Therefore, the average current drawn from the stack is 9.4 A. The open circuit voltage (V_{oc}) of the stack is 24.75 V. For the 5-cell stacks, the flow rates of H_2, N_2 and air are 1.9 slpm, 0.33 slpm and 7.65 slpm, respectively. The air inlet temperature is kept at 800°C and the core temperature is 850°C.

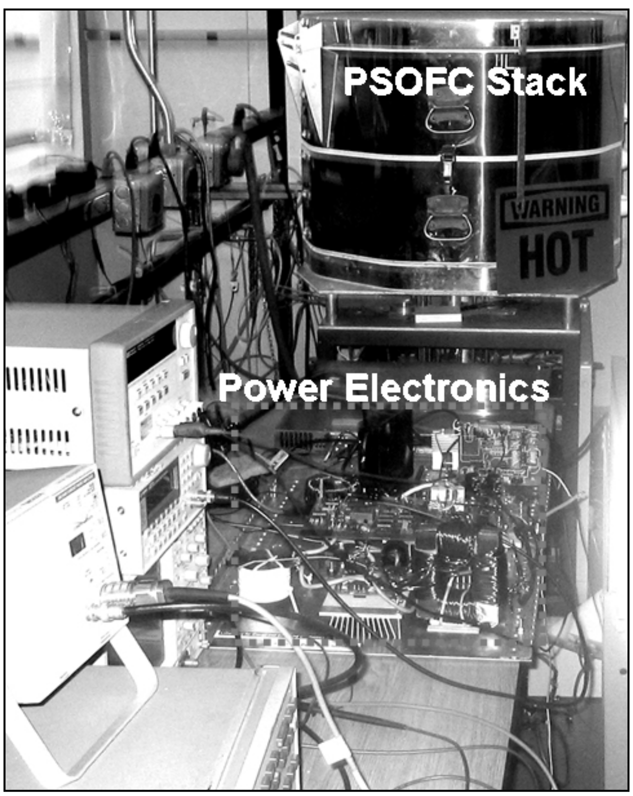

FIGURE 1. Experimental Setup of the 25 Cell PSOFC Stack with the PES

Based on the electrical-feedback analyses, a novel patent-pending topological power-management controlling strategy and architecture for a SOFC PCS has been designed. This improves steady-state energy efficiency of the PES (almost flat efficiency across the power range as compared to progressively drooping efficiencies as in conventional case) and hence the PCS by optimizing the fuel utilization in the stack in the steady-state. Further, using a multi-loop feedback, the control also integrates to a battery-buffer control to mitigate the effect of the load transient on the SOFCS (e.g., fuel utilization). A new methodology has also been developed to systematically relinquish the control of the battery (after transience phases out) at a rate governed by the control bandwidth of the BOPS.

To determine the optimal synthesis/design and dynamic operation of the SOFC system, a parametric system optimization is conducted. This requires the optimal synthesis/design and dynamic operation of each of the BOPS subsystems to be carried out in an integrated fashion, leading to the establishment of a feasible system super-configuration which provides high efficiency and reliability. The results of the parametric studies based on the super-configuration were used to determine the most promising subset of this super-configuration based on system response, fuel consumption, capital cost, operational constraints, etc. The resulting reduced super-configuration was subjected to a large-scale synthesis/design optimization while taking into account its effects on system operation, i.e., on the dynamic response of the system. The parametric studies showed this configuration to provide adequate fuel efficiency.

Results

Figures 2a and 2b show the drop in the output voltage of the stack model and the experimental stack prototype, respectively, due to the subjected load transient of 2 A to 12 A. This also leads to an increase in the mean temperature of the stack.

The effect of the ripple is validated using a sinusoidally modulated bidirectional DC-DC converter connected across the stack. The current drawn from the stack contains LF ripple with frequency (120 Hz) twice that of the sinusoidal AC (60 Hz) output. Figures 3a and 3b show the effect of a LF (120 Hz) ripple on the 1-D stack model and the experimental prototype, respectively.

To achieve very high efficiency, the stack must be operated at a particular current level (this corresponds to the maximum operable fuel utilization) as shown in Figure 4. However, due to the presence of LF ripple in the stack current, the operating mean stack current has to be decreased, to avoid zero-reactant condition, as illustrated in Figure 4.

Due to non-unity power factor of the load, the ripple in the stack current increases. This ripple further depends on the output capacitance connected across

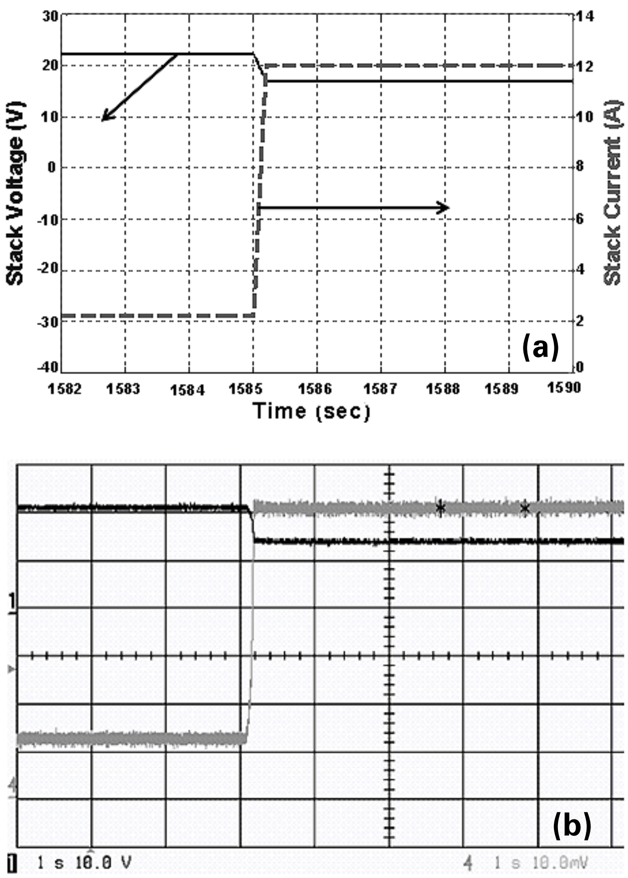

FIGURE 2. (a) Effect of Load Current Transient (2.2 A to 12 A) on the Voltage of the Stack Model; (b) The Experimental Validation of Its Effect on the Planar Stack; Scope Channel 1 (10 V /div) and Channel 4 (2 A/div) Measure the Stack Voltage and Current, Respectively

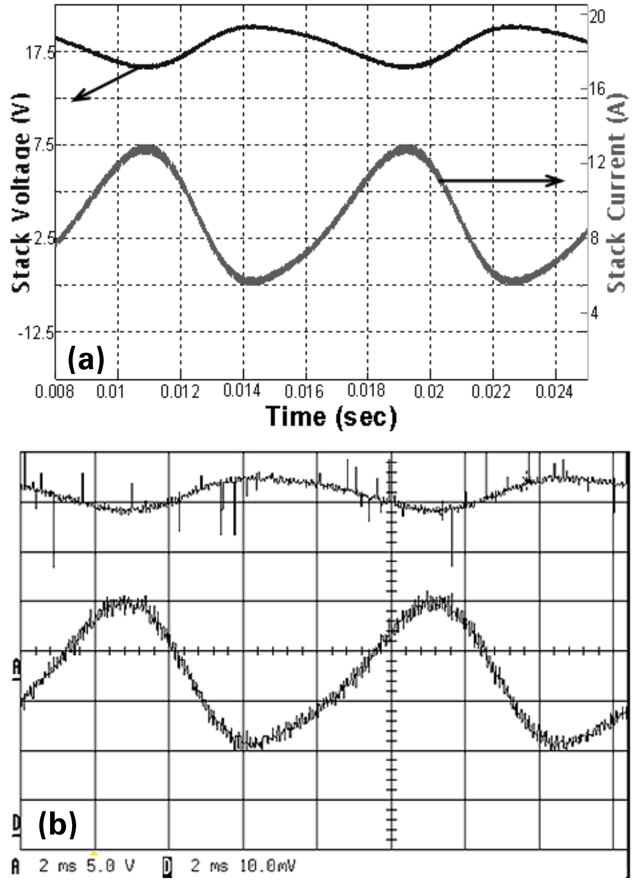

FIGURE 3. (a) Effect of 40 Percent Current Ripple on the Stack Voltage of 1-D Model; (b) Experimental Validation of the Ripple Effect on Planar SOFC Stack; Scope Channels A and D Show the Stack Voltage and Current, Respectively

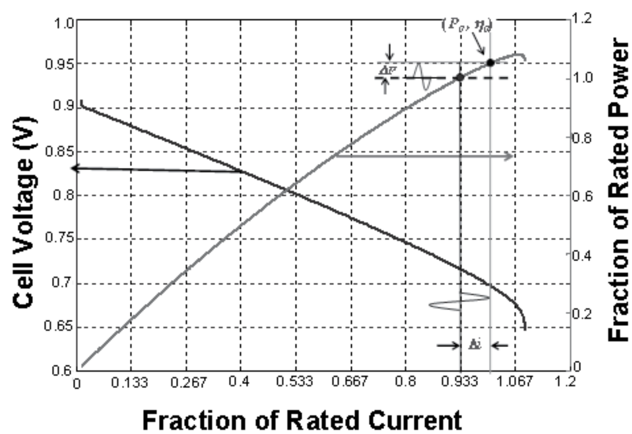

FIGURE 4. Effect of LF Ripple on the Performance and Efficiency of the Stack

the DC bus. Figure 5 shows the effect of load power factor variations on the stack current ripple at various capacitances and at a constant active power drawn by the load. Therefore, a decrease in the load power factor decreases the efficiency of the stack. However, the increase in the mean temperature is minimal.

An increase in the harmonic distortion of the AC load increases the distortion in the output ac current due to increase in the magnitude of the harmonic components as well their phase. This distortion in the AC current also introduces distortion in the current drawn from the planar stack. At a fixed power factor of the fundamental current, the ripple in the stack current decreases with an increase in the total harmonic distortion (THD) of the load.

Figure 6 shows the percentage degradation of the ASR (area specific resistance) in the stacks after approximately 900 hours of study due to the load transient and the LF ripple. This shows that, the degradation of the ASR due to the load transient is very high as compared to the stack carrying constant current. Similarly, increase in the ASR of the stack with LF ripple current is higher as compared to the stack feeding constant current.

Finally, the response of the designed power management system is investigated. The PCS is subjected to a load transient at time t = 0.02 second. As a result, the stack output current increases to meet the new load demand. However, the increase in the battery current prevents the surge in the stack current, and stabilizes the stack voltage close to its nominal value. Figure 7a shows the response of the battery current after the load transient with BOPS flow adjustments. Since the current drawn from the stack is independent of the load current, the fuel utilization of the stack remains unaltered as shown in Figure 7b. Hence, this completely alleviates the effect of the load transient on the fuel cell stack.

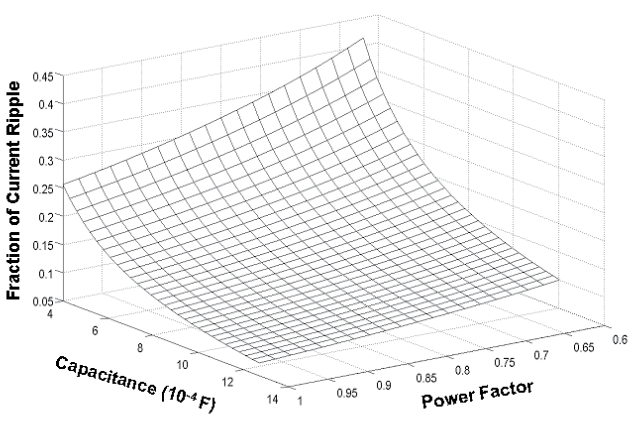

FIGURE 5. Effect of Power Factor of the Load on the Magnitude of Stack Current Ripple

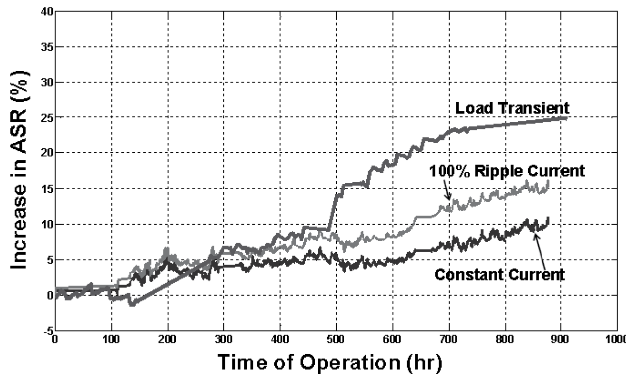

FIGURE 6. Comparison of Long-term ASR Degradation Due to LF Ripple, Constant Current and Load Transient

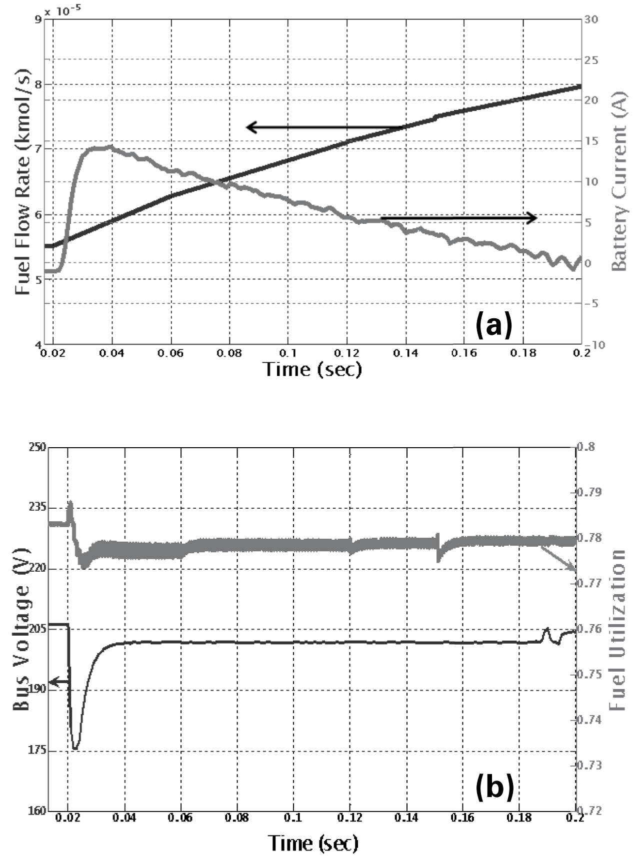

FIGURE 7. (a) Response of the Battery Current to a Sudden Load Transient Which Is Followed by the Flow Adjustment of BOPS; (b) Response of the Bus Voltage and Fuel Utilization to a Sudden Load Transient Which Is Followed by the Flow Adjustment of BOPS

Conclusions

A comprehensive investigation of several different electrical feedbacks induced due to the power electronics subsystem (PES) and the application load (AL), which may potentially affect the performance and durability of planar solid-oxide fuel cell stack (PSOFCS), was conducted. The accuracy of the model and their ability in determining the effects of several electrical feedbacks on PSOFC during the transient and in the steady state were experimentally validated. Using the validated model, accurate estimations of the impacts of several electrical feedback effects on the performance and durability of the PSOFC PCS were conducted using parametric study. An experimental degradation study was done to estimate the long-term effects of the load transient and the ripple on the performance of the stack. Specifically, the following conclusions were drawn:

- The no-load to full-load transient increases the current density in the planar fuel cell abruptly and immediately. The higher level of current density increases the fuel utilization and the polarization voltage leading to a drop in the cell voltage. This change in the fuel utilization is detrimental to the cell performance and efficiency.
- The load transient not only increases the mean temperature but also changes the spatial distribution of stack temperature. This variation depends on the magnitude of the current transient and is independent of the slew rate of the transient. The load transients accelerate the degradation of the ASR of the planar cell. Therefore, they deteriorate the efficiency of the stack. To prevent this, suitable energy buffering techniques should be available to eliminate the effect of the load transient from the stack.
- The higher ripple current magnitude in the stack current forces a decrease of the operating fuel utilization of the stack, and hence, lowers the stack efficiency. However, this has negligible impact on the stack temperature. In the long-term, the ripple current accelerates the degradation of the ASR, deteriorating the efficiency of the stack.
- Lower power factor of the load increases the magnitude of current ripple drawn from the stack, and this reduces the efficiency of the stack. The effect of the load power factor on the stack temperature is minimal.
- Higher THD of the AC load decreases the magnitude of current ripple drawn from the stack. However, it has negligible impact on the stack temperature.

The parametric study provided a detailed insight into the effects of several electrical-feedback effects on the planar solid-oxide fuel cell (PSOFC) stack and the PSOFC power conditioning system (PCS) as a whole. This facilitates the design of control and optimization of PSOFC PCS parameters towards the achievement of a highly-efficient and reliable power system.

Determination of the optimal synthesis/design of the BOPS was done using optimal synthesis/design and dynamic operation of each of the auxiliary power unit subsystems in an integrated fashion. For the individual subsystems, the proposed dynamic iterative local-global optimization approach provides optimal configurations even in the strictest of the transients, optimizing the system cost and performance.

The efficiency of the power converter system was maximized using efficient power sharing. The control strategy completely eliminates the effect of the load transient on the fuel cell stack by providing the additional load current from the battery. Secondly, in the steady-state it maximizes the efficiency of the system by optimizing the fuel utilization in the stack. Based on the strategy designed here, a planar solid-oxide fuel cell based power conditioning system shows a remarkable increase in efficiency.

References

1. Hsiao, Y. C., and Selman, J. R., 1997, "The Degradation of SOFC Electrodes," *Proceedings of Solid State Ionics*, vol. 98, pp. 33-38.

2. Huang, X., and Reifsnider, K., 2001, "Modeling Long-Term Performance of Solid Oxide Fuel Cells: A Phenomenological Approach," *15th Annual Conference of Fossil Energy Material*s, Knoxville, TN.

3. Achenbach, E., "Response of a Solid Oxide Fuel Cell to Load Change," *Journal of Power Sources*, vol. 57, pp. 105–109, 1995.

4. Gemmen, R. S., 2003, "Analysis for the Effect of Inverter Ripple Current on Fuel Cell Operating Condition," *Journal of Fluids Engineering*, vol. 125, issue 3, pp. 576-585.

5. Hartvigsen, J., Elangovan, S., and Khandkar, A., 1993, *Science and Technology of Zirconia V*, Edited by Badwal, S., Bannister, M., and Hannink, R., Technomic Publishing Company, Inc., Lancaster, Pennsylvania.

6. Yakabe, H., Ogiwara, T., Hishinuma, M., and Yasuda, I., 2001, "3D Model Calculation for Planar SOFC," *Journal of Power Sources*, 102, pp. 144-154.

7. S.K. Mazumder, S. Pradhan, J. Hartvigsen, M. von Spakovsky, and D. Rancruel, "Effects of battery buffering and inverter modulation on the post load-transient performance of planar solid-oxide fuel cell", *IEEE Transactions on Energy Conversion*, in press for publication, 2006.

8. Mazumder, S.K., Acharya, K., Haynes, C.L., Williams, R., von Spakovsky, M. R., Nelson, D. J., Rancruel, D. F., Hartvigsen, J., and Gemmen, R. S., 2004, "Solid-Oxide-Fuel-Cell Performance and Durability: Resolution of the Effects of Power-Conditioning Systems and Application Load," Special Issue on Distributed

Generation, *IEEE Transactions of Power Electronics*, vol. 19, pp. 1263-1278.

FY 2006 Publications/Presentations

1. S. K. Pradhan, S.K. Mazumder, J. Hartvigsen, M. Hollist, "Effects of electrical feedbacks on planar solid-oxide fuel cell", *ASME Journal of Fuel Cell Science and Technology,* accepted for publication, 2006.

2. R.K. Burra, S.K. Mazumder, "A ripple-mitigating and energy-efficient fuel cell power-conditioning system", *IEEE Transaction of Power Electronics*, accepted for publication, 2006.

3. S.K. Mazumder, S. K. Pradhan, J. Hartvigsen, M. von Spakovsky, and D. Rancruel, "Effects of battery buffering and inverter modulation on the post load-transient performance of planar solid-oxide fuel cell", IEEE Transactions on Energy Conversion, in press for publication, 2006.

Special Recognitions & Awards/Patents Issued

1. S.K. Mazumder, S. K. Pradhan, and R. K. Burra, A novel power-management control for fuel cell power conditioning system, USPTO Provisional Patent Filing #CZ029, November 2005.

2. S. K. Mazumder, R. K. Burra, and K. Acharya, A novel efficient and reliable dc-ac converter for fuel cell power conditioning, USPTO Patent Application# 20050141248, September 2004.

3. Dr. Mazumder presented the Keynote Lecture on fuel cell power electronics at the ASME Third International Conference on Fuel Cell Science, Engineering and Technology, held at Yipsilanti, Michigan between May 23–25, 2005.